Performance Summary of the ESS Phase Reference Line

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On behalf of the WUT and ESS PRL Team

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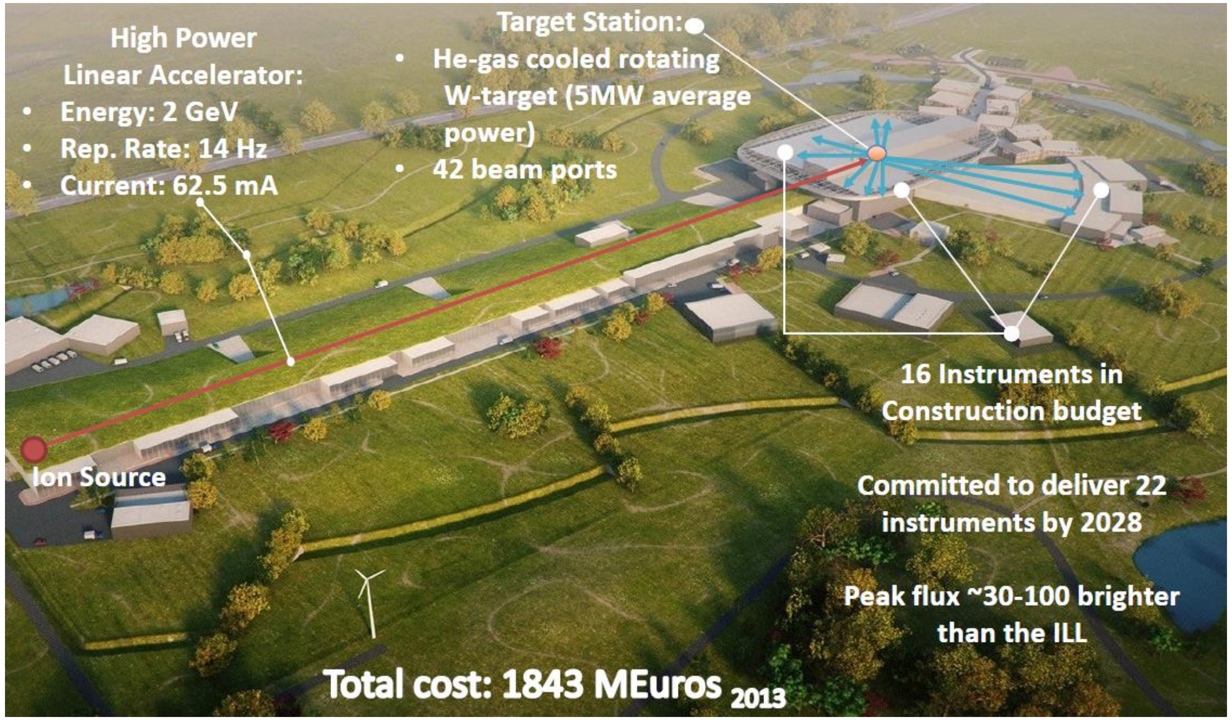
WUT Contributions to European Spallation Source (Polish In-Kind)

- **Phase Reference Line (PRL)***
- MTCA. 4 based ESS LLRF control system components# (Member of the Polish Electronic Group)
- RF electronics and cabling design, installation and tests for the Beam Diagnostics

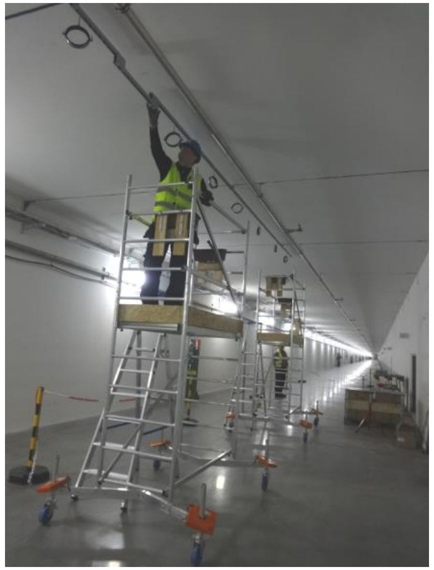


*Czuba Krzysztof et. al.: *Concept of the Phase Reference Line for the European Spallation Source*, MIKON 2018, Poznań, Poland ISBN 978-83-949421-0-6, ss. 512-514.

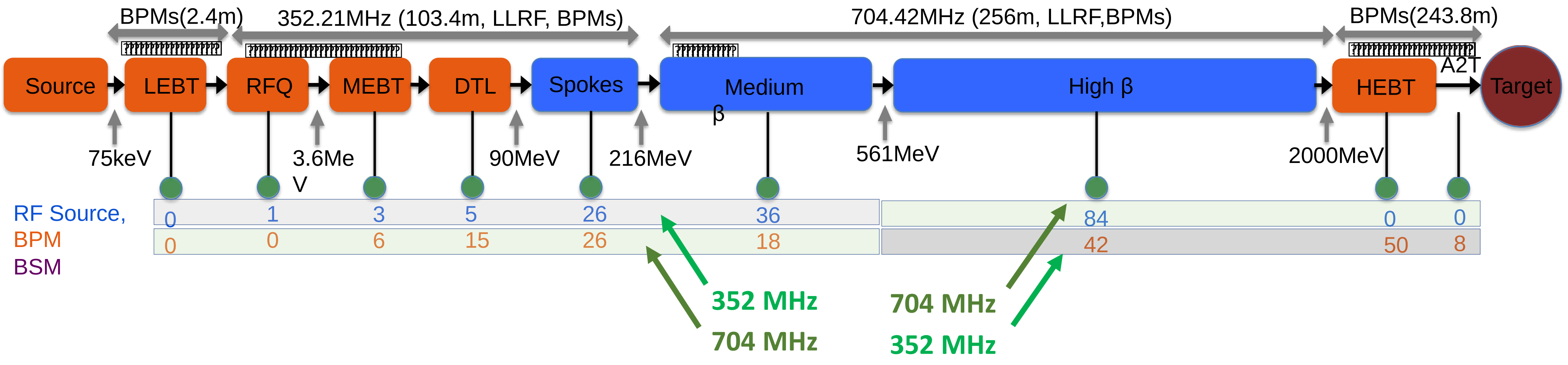
#J. Szewiński et al., "*Contribution to the ESS LLRF System by Polish Electronic Group*", IPAC2017, Cpenhagen, Denmark.

A Brief History

- Officially started in October 2016
- Basic concept by ESS (general requirements) and the Lund University (temp. control)
- Originally planned a single frequency distribution line with a simple power splitter at each Tap Point, **well …**
- Developed to the final shape after building 18.7m long **prototype in a WUT corridor**
- WUT team was the first to start installations in the ESS tunnel in July 2017
- Installation almost* completed in late 2021
- * Currently under final tests after other installations finished by ESS



ESS RF Phase Synchronization Requirements

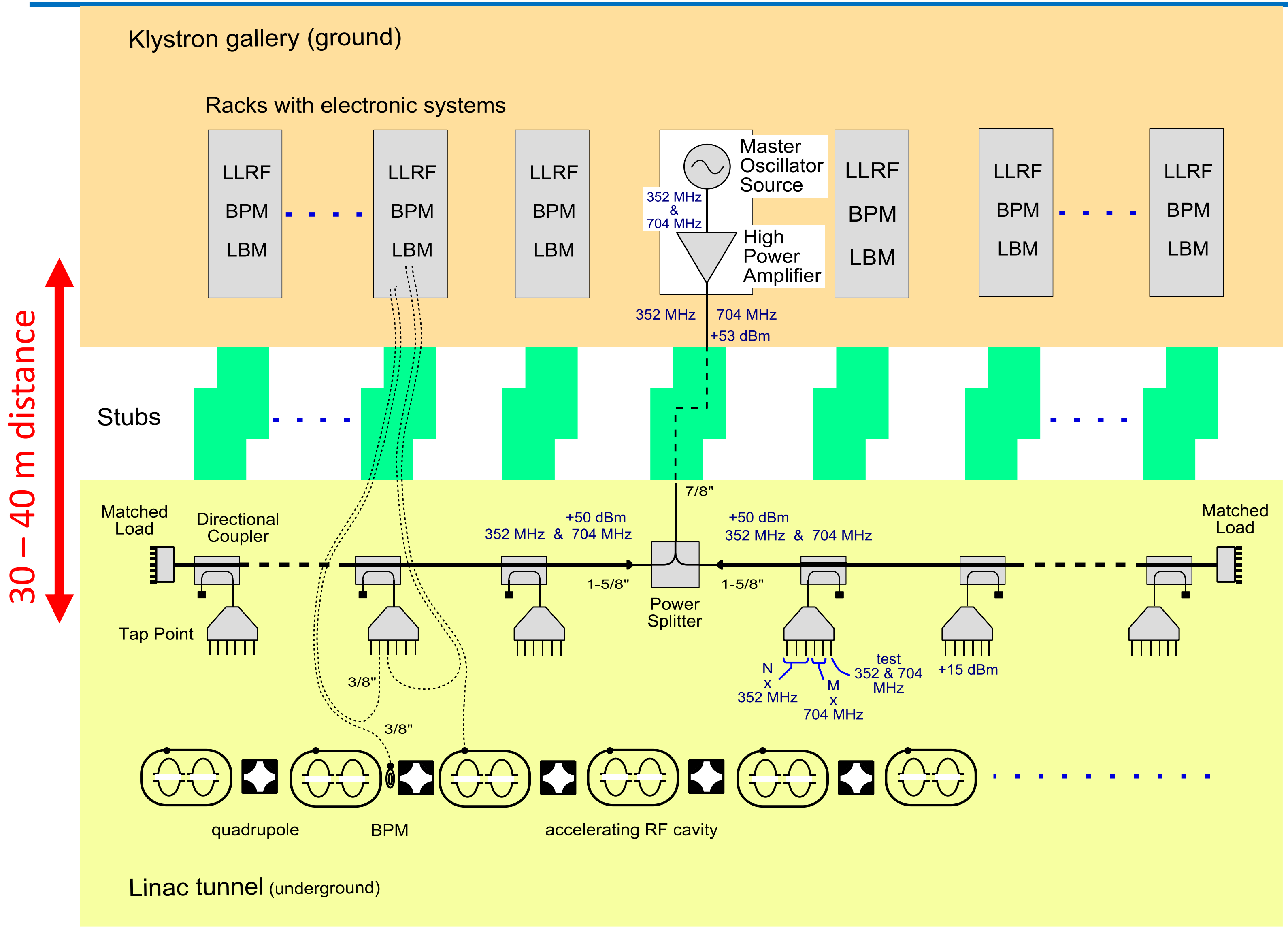


- Both 352 MHz and 704 MHz required along the entire linac **(drift reduction)**
- Required phase synchronization:
  - 0.1° for short term (during 3.5 ms pulse),
  - 0.1° for long term between adjacent outputs
  - 2.0° for long term (hours to days)

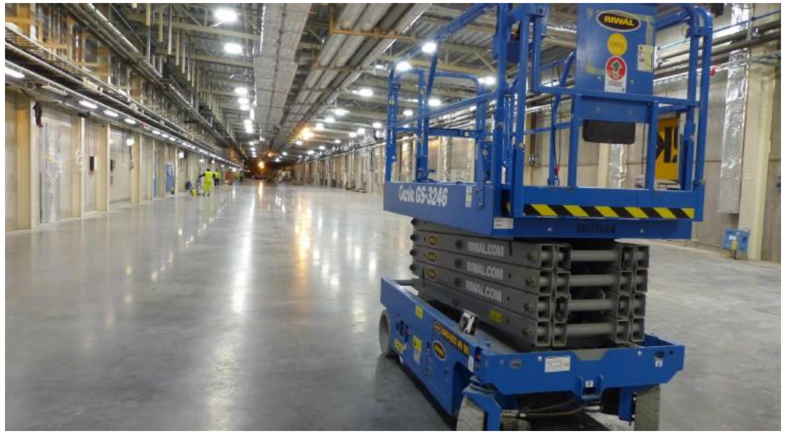
Main Assumptions for the Phase Reference Line

- Passive distribution along the accelerator tunel (radiation)
- **Single** 1/5” coaxial rigid line **for 352 MHz and 704 MHz**
- 58 signal taps (3 or 6 way), 294 total outputs
- Frequency selective, configurable tap outputs
- Equal power level at each output (+17 dBm +/- 1 dBm), at both frequencies – **min. +14 dBm for most of devices**
- Temperature and internal gas (Nitrogen) pressure control
- All active electronics in the Klystron Gallery hall

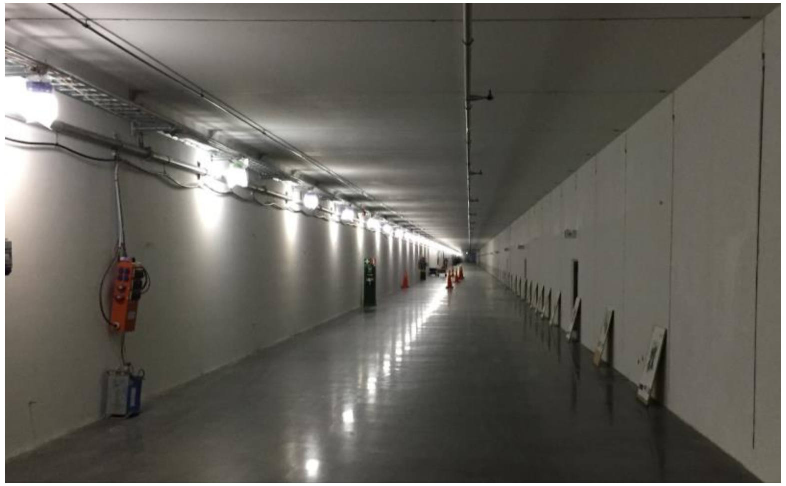
PRL RF Scheme



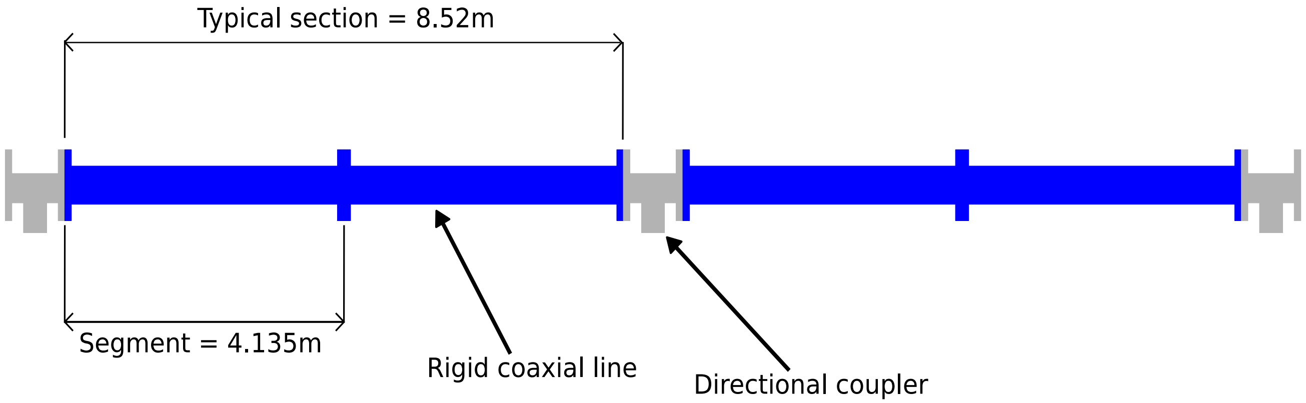
Klystron Gallery before installations



Tunnel before installations



Main Line Design

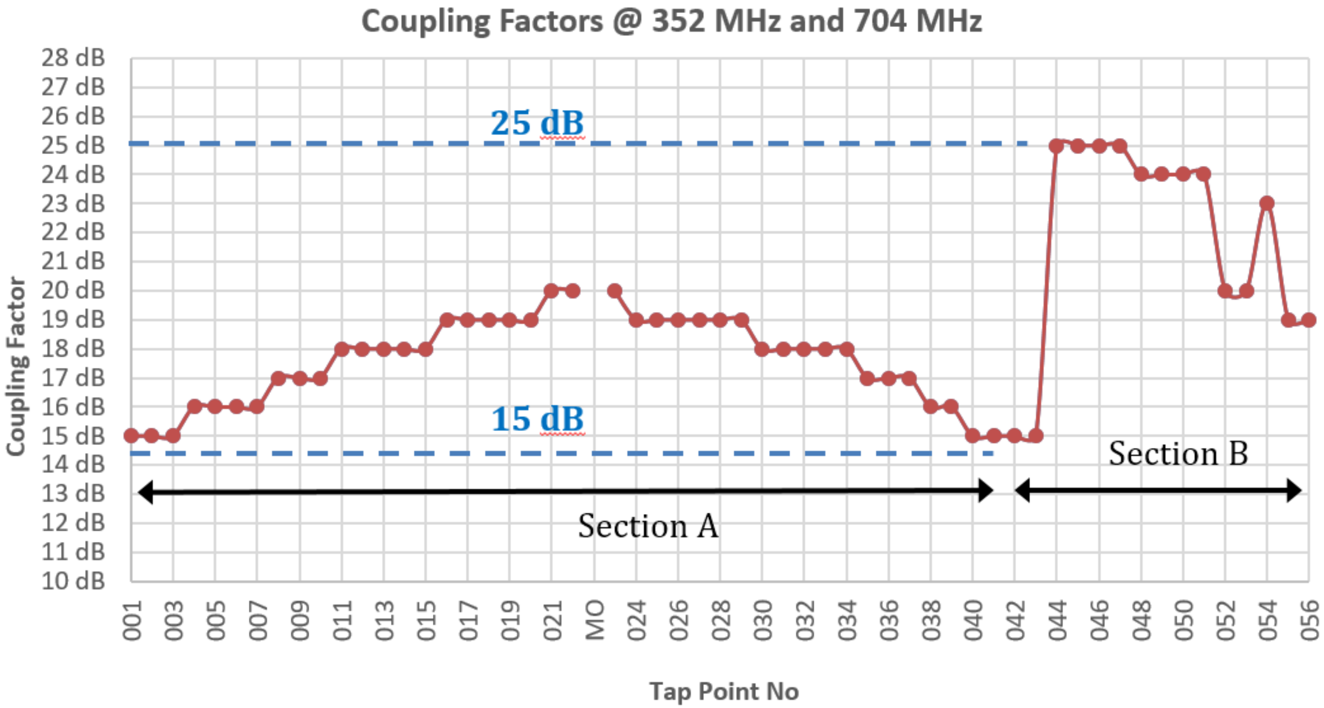


No of 4.135m segments in section	No. of sections	Total no of segments	Total segment length [m]
2	37	74	305,990
3	3	9	37,215
4	7	28	115,780
5	2	10	41,350
6	2	12	49,620
	51	133	549,955
Irregular segments	5		38,700

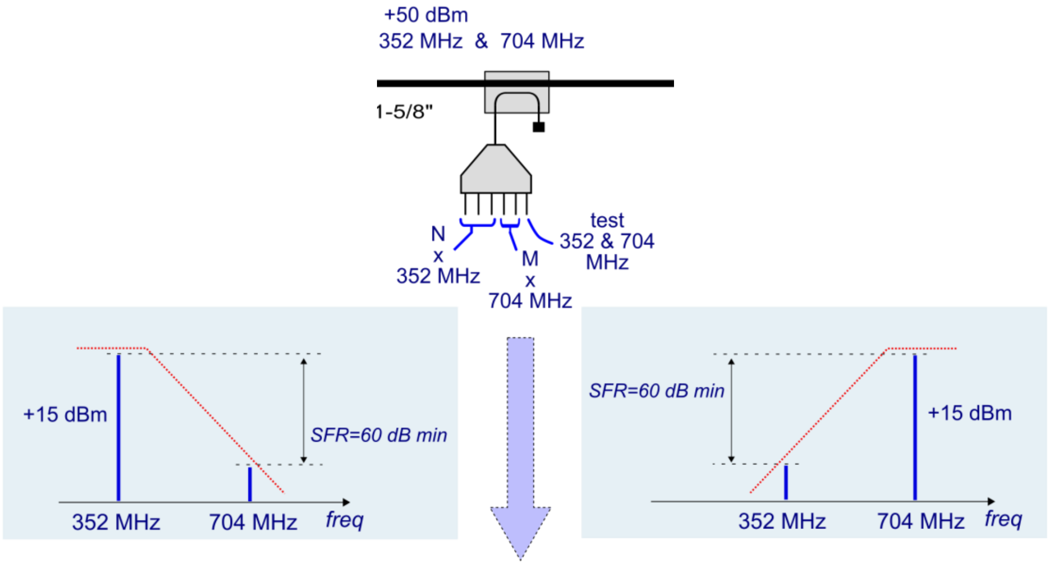
- Modular design to simplify production and assembly
- Minimized of number of various segment types
- Teflon free line supports
- Gas tight system

Directional Couplers

- Directional coupler with adjustable coupling factor, the same @ both 352 MHz and 704 MHz
- Minimized number of coupling factors along the tunnel

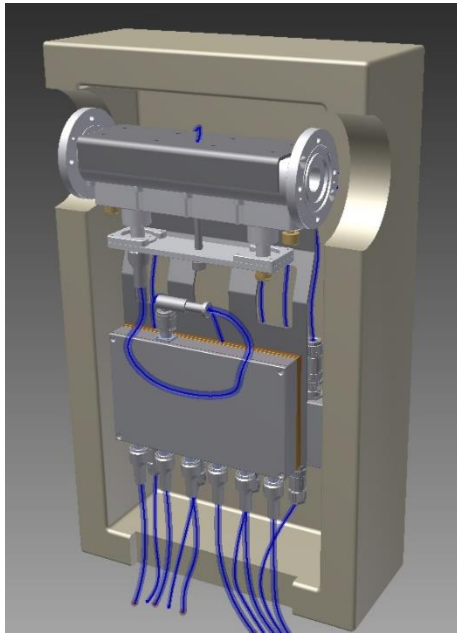


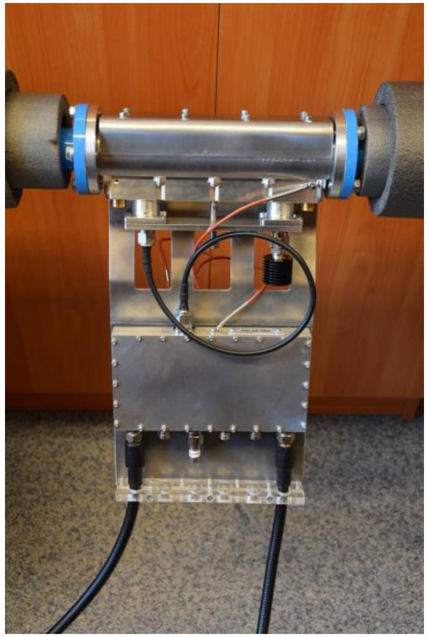
Design by the Space Forest company

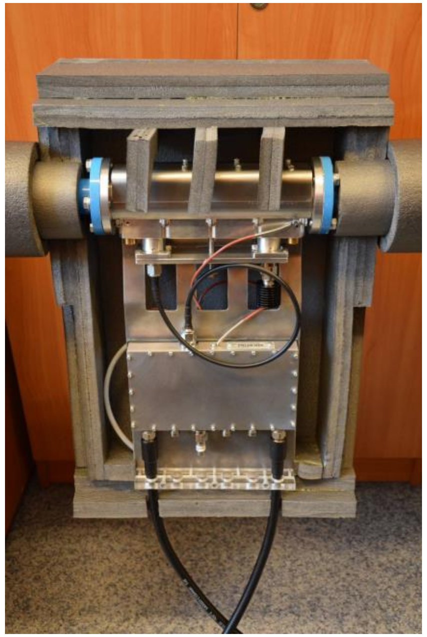


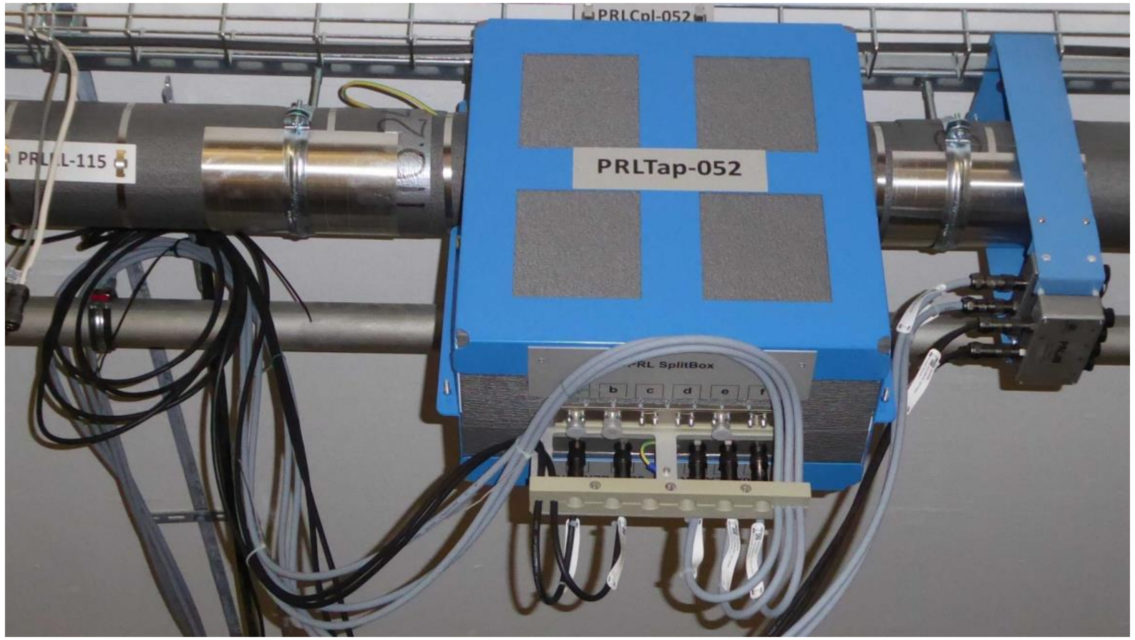
Tap Point

1. Coaxial directional coupler + PRL Split Box + Junction Boxes (J-Box)
2. Temperature stabilization (+/- 0.1 ^{o}C)
3. Mechanics for temperature stabilization and mechanical stress relief
4. Produced and installed 58 pieces



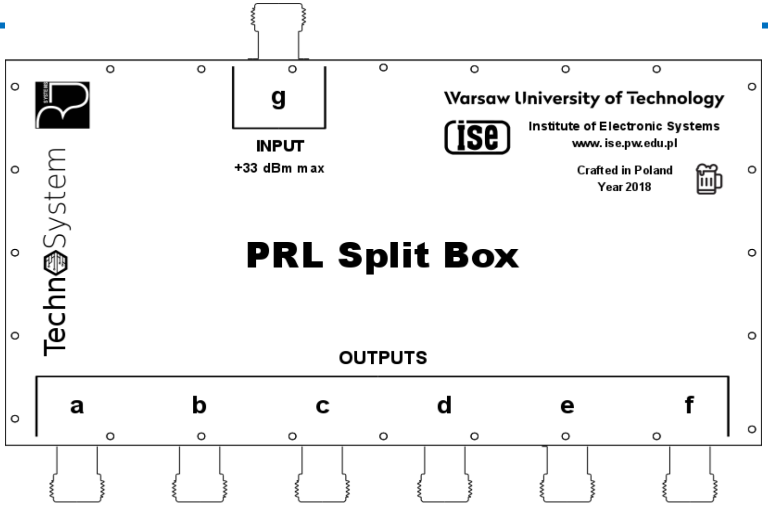


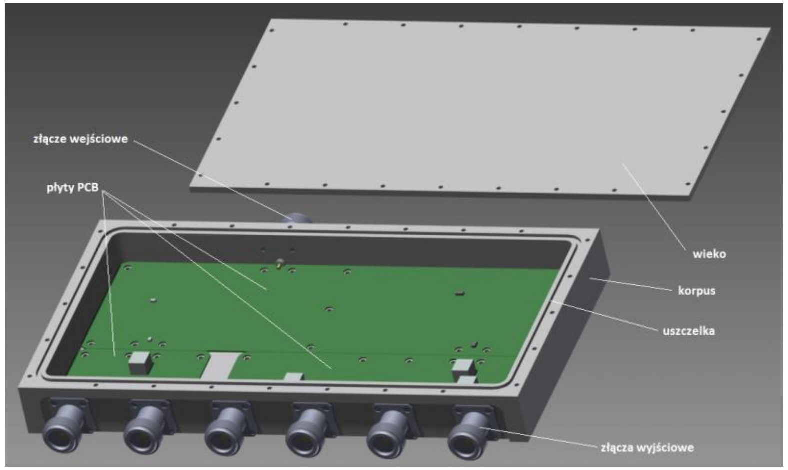


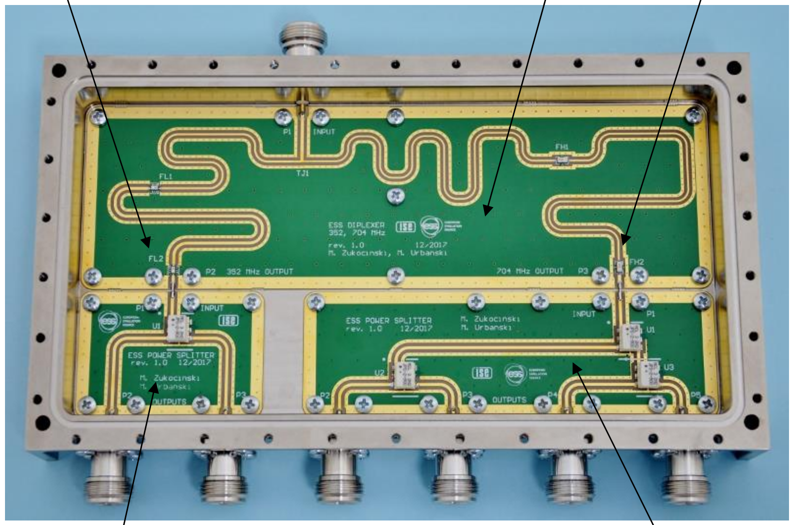


PRL Split Box for TapPoints

- Passive (RF diplexer + power splitter) structure allowing for flexible configuration of output frequencies for up to 6 outputs
- Produced 60 pieces







RF Split Box	assembly configuration (PCBs)	OUTPUTS a	b	c	d	e	f
RF Split Box-001	4+2	LLRF 352 MHz	LLRF 352 MHz	LLRF 352 MHz	spare 352 MHz	BPM 704 MHz	BPM 704 MHz
RF Split Box-002	2+4	LLRF 352 MHz	LBM 352 MHz	spare 704 MHz	spare 704 MHz	BPM 704 MHz	BPM 704 MHz
RF Split Box-003	2+4	LLRF 352 MHz	spare 352 MHz	spare 704 MHz	BPM 704 MHz	BPM 704 MHz	BPM 704 MHz
RF Split Box-004	1+1	LLRF 352 MHz	X	X	X	BPM 704 MHz	X
RF Split Box-005	1+1	LLRF 352 MHz	X	X	X	BPM 704 MHz	X
RF Split Box-006	1+1	LLRF 352 MHz	X	X	X	BPM 704 MHz	X
RF Split Box-007	1+1	LLRF 352 MHz	X	X	X	BPM 704 MHz	X
RF Split Box-008	1+1	LBM 352 MHz	X	X	X	BPM 704 MHz	X
RF Split Box-009	4+2	LLRF 352 MHz	LLRF 352 MHz	LLRF 352 MHz	LLRF 352 MHz	spare 704 MHz	BPM 704 MHz
RF Split Box-010	4+2	LLRF 352 MHz	LLRF 352 MHz	LLRF 352 MHz	LLRF 352 MHz	spare 704 MHz	BPM 704 MHz
RF Split Box-011	4+2	LLRF 352 MHz	LLRF 352 MHz	LLRF 352 MHz	LLRF 352 MHz	spare 704 MHz	BPM 704 MHz
RF Split Box-012	4+2	LLRF 352 MHz	LLRF 352 MHz	LLRF 352 MHz	LLRF 352 MHz	spare 704 MHz	BPM 704 MHz
RF Split Box-013	4+2	LLRF 352 MHz	LLRF 352 MHz	LLRF 352 MHz	LLRF 352 MHz	spare 704 MHz	BPM 704 MHz
RF Split Box-014	4+2	LLRF 352 MHz	LLRF 352 MHz	LLRF 352 MHz	LLRF 352 MHz	spare 704 MHz	BPM 704 MHz
RF Split Box-015	4+1	LLRF 352 MHz	LLRF 352 MHz	LBM 352 MHz	spare 352 MHz	spare 704 MHz	X
....	....	....	....	....	....	....	....

PRL Output Power Levels

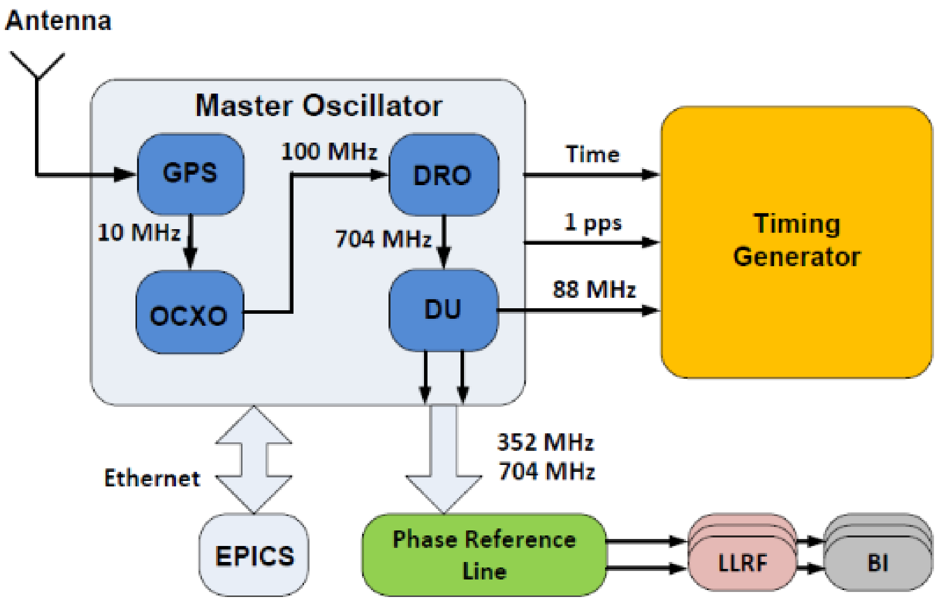
Output type	Required power levels [dBm]		Measured power levels [dBm]	
	Minimum	Maximum	Minimum	Maximum
BPM 352.21 MHz	14.0	25.0	22.7	23.7
BPM 352.21 MHz @PRLTap-046 – 058	10.8	25.0	11.0	16.2
BPM 704.42 MHz	14.0	25.0	17.7	18.4
BPM 704.42 MHz @PRLTap-005 – 008	10.8	25.0	13.0	13.5
BPM 704.42 MHz @PRLTap-004	7.7	25.0	8.8	9.1
LLRF 352.21 MHz	14.0	18.0	15.5	16.2
LLRF 704.42 MHz	14.0	18.0	13.7*	15.0
LBM 352.21 MHz	14.0	25.0	15.7	23.5

- *Power level at 7 outputs 0,3 dBm below specs - additional outputs were requested during installation
- No issue, thre is still a safety margin

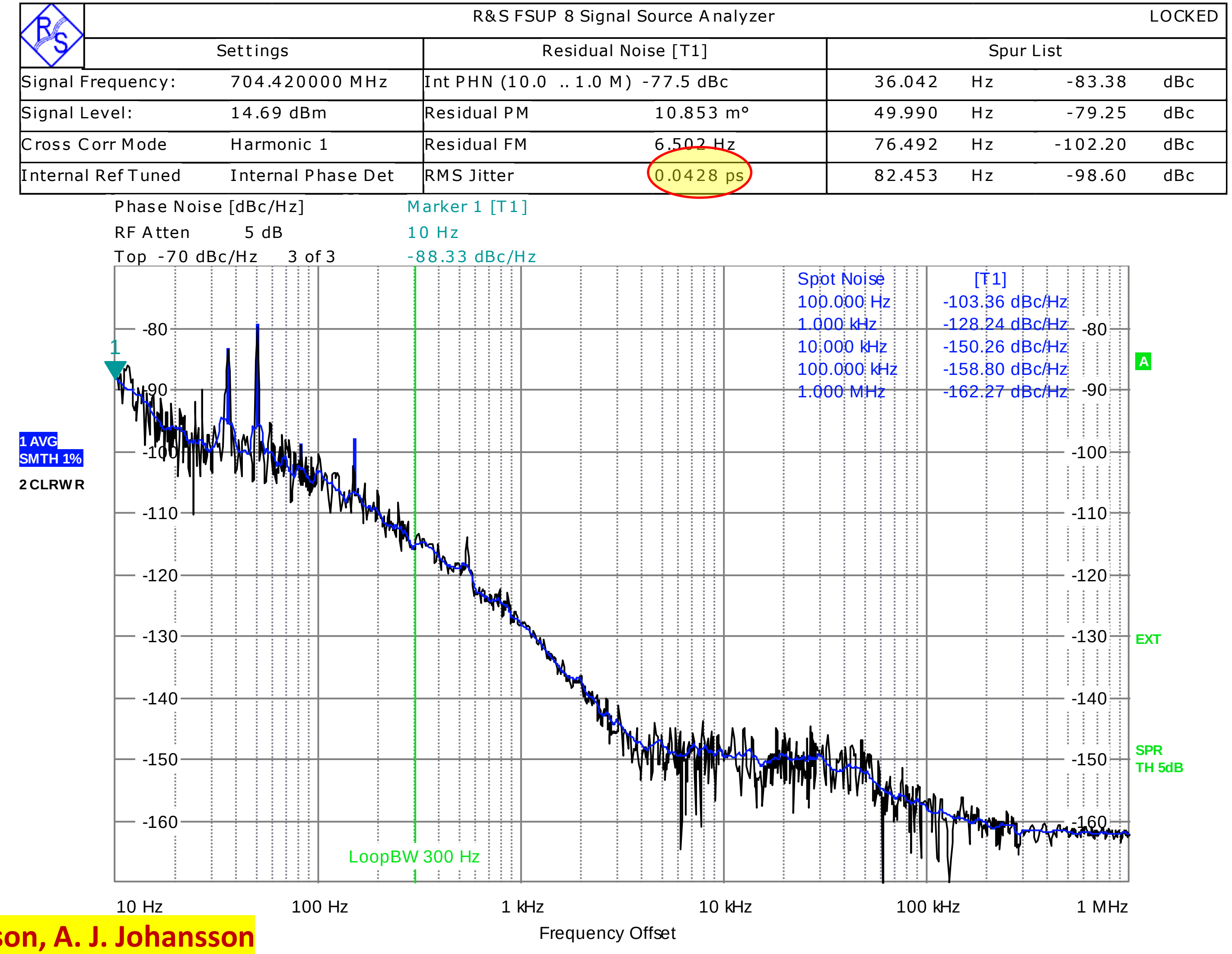
Harmonics of all output signals within specs(< -60 dBc):

- worst case: 63.0 dBc
- best case: 69.4 dBc

Master Oscillator



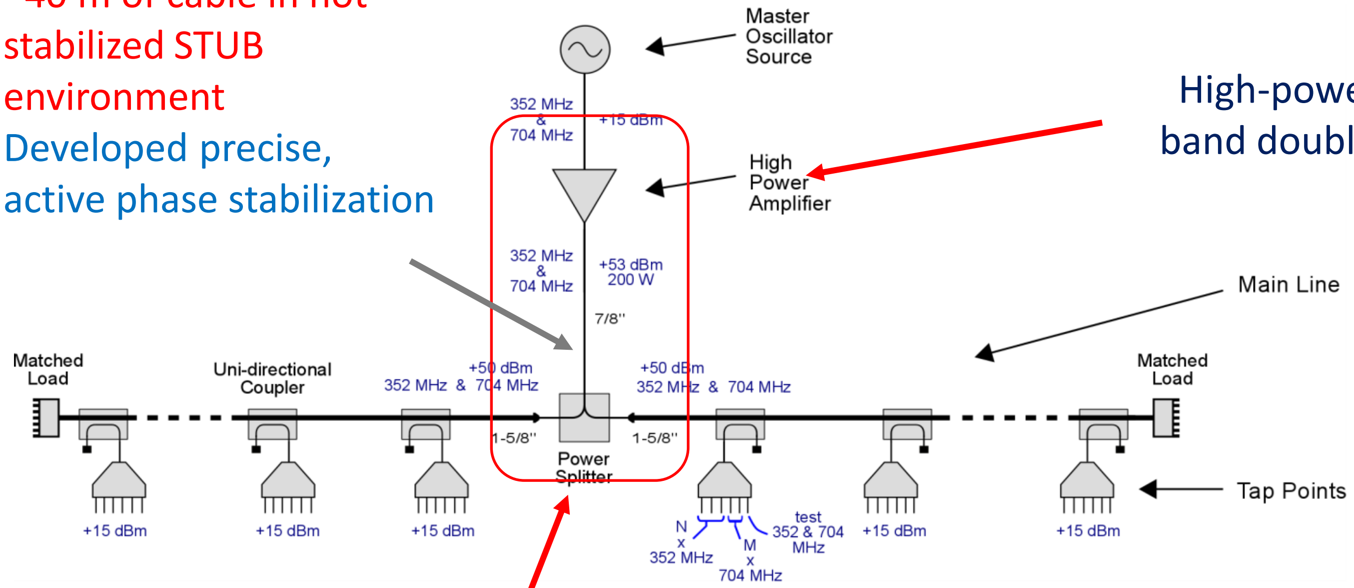
- Design by Lund University and ESS
- Output power +6.3 dBm
- RMS Jitter **laboratory** test (10 Hz – 1 MHz):
  - ~ 80 fs @ 352 MHz
  - ~43 fs @ 704 MHz
- **Final test in accelerator to be performed**



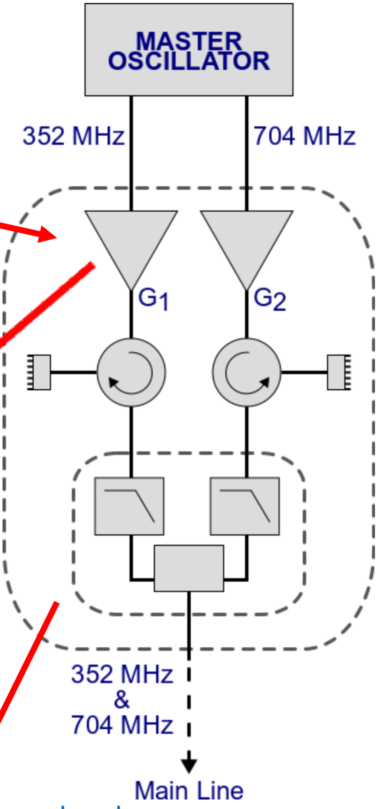
Courtesy of A. Svensson, A. J. Johansson

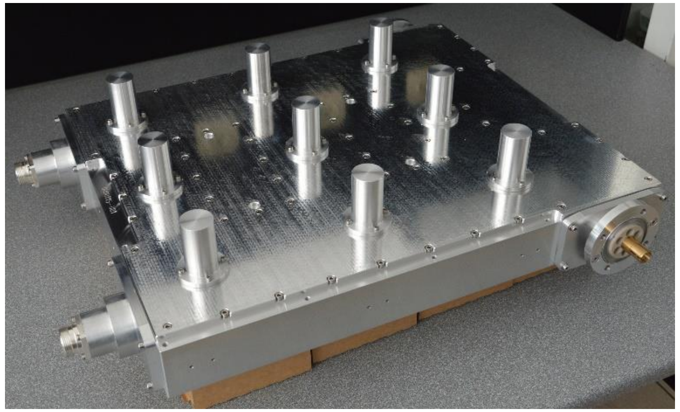
PRL Input Section

- ~40 m of cable in not stabilized STUB environment
- Developed precise, active phase stabilization



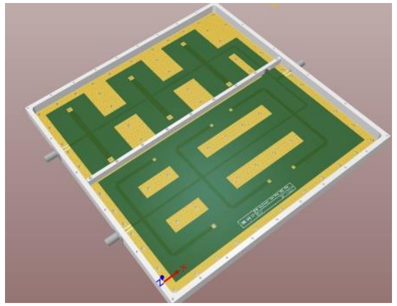
High-power (~200W) broad band double amplifier system



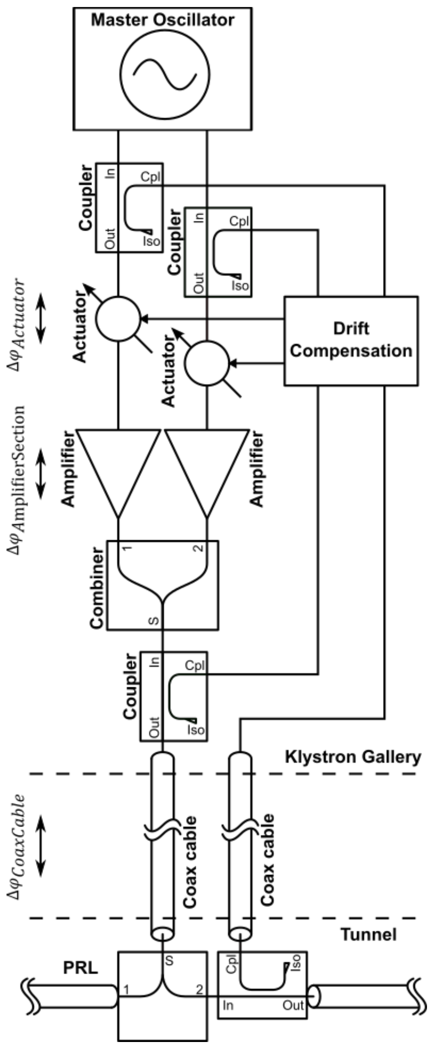


Input power splitter by the Space Forest company

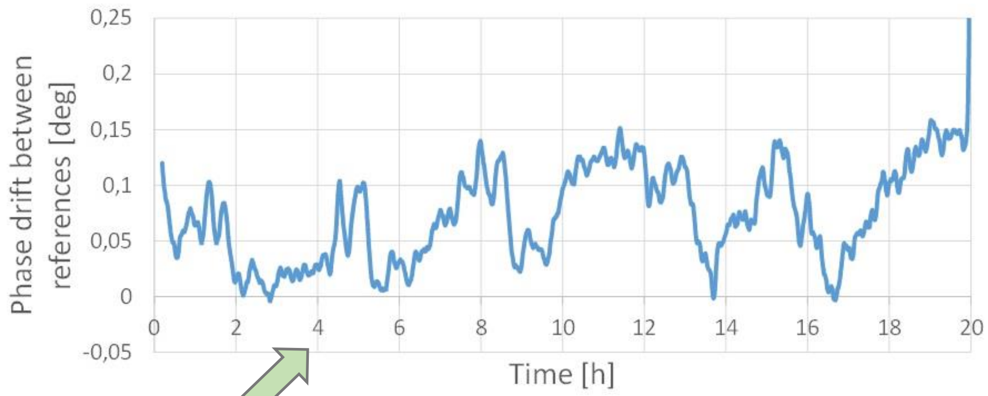
Bandpass combiner designed and produced at WUT

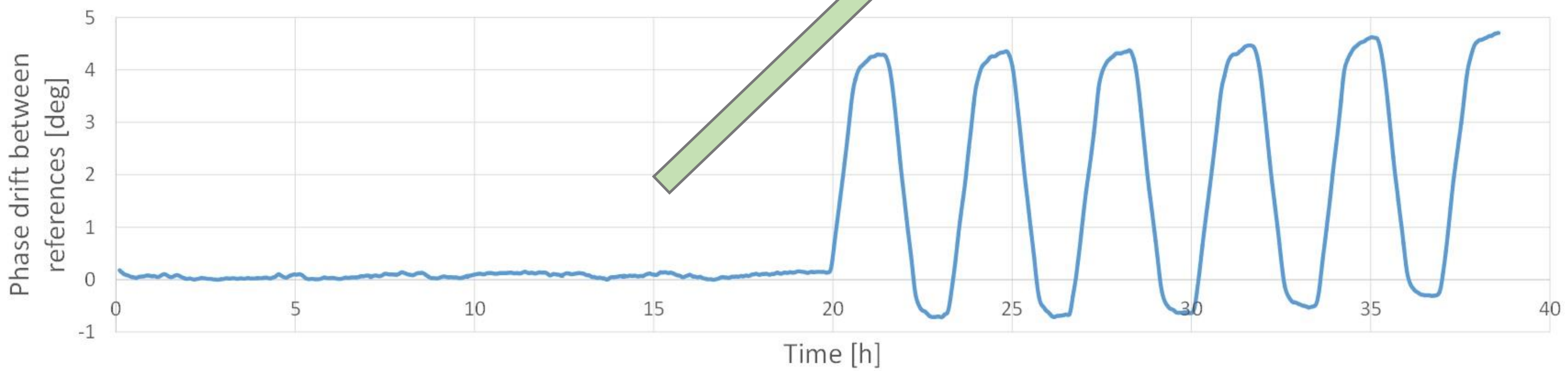


PRL Input Section Drift Compensation



- PRL PDC – compensation of phase drift between the MO and PRL line in the tunnel (**long cable, no temperature stabilization**)
- Laboratory tests: 0.15 deg p-p of phase stability
- Waiting for possibility of testing in ESS

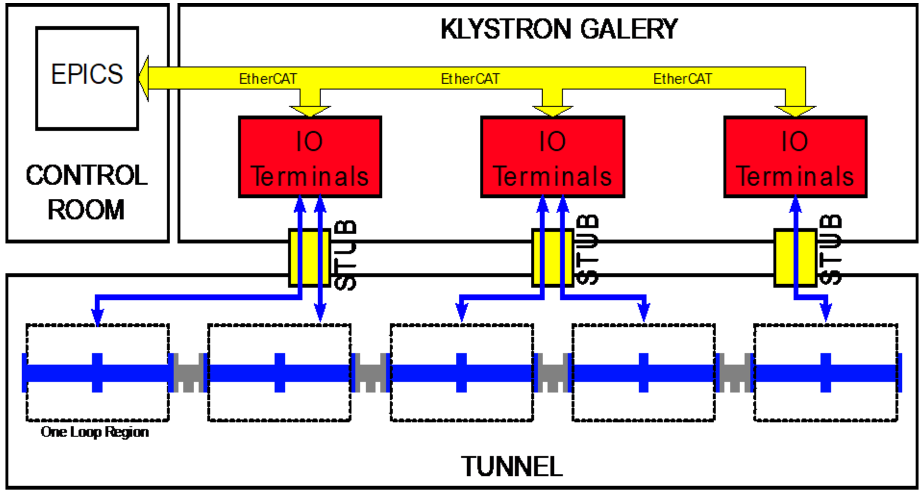


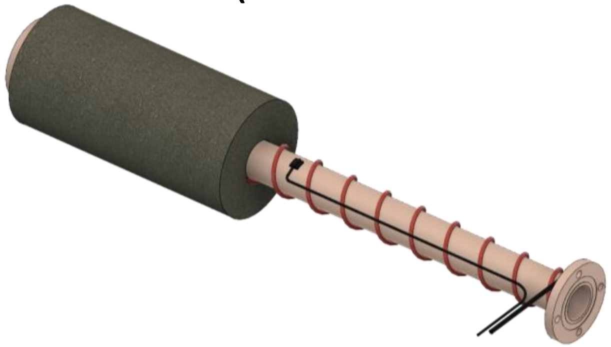


Courtesy of D. Sikora

Temperature Control System

- Regulation to +/- 0.1 ^{o}C, 600 m line + 58 Tap Points!
- Line is wrapped with a **heating tape and a thermal insulation**
- Industrial temperature controllers – basic selection and general concept by Lund University (Björn Olofsson)
- 202 independent temperature control loops
- Control software running on EPICS servers
- Concept successfully tested in PRL prototype at WUT
- A lot of logistics, tests and quality control needed (over 6000 internal cable connections …)

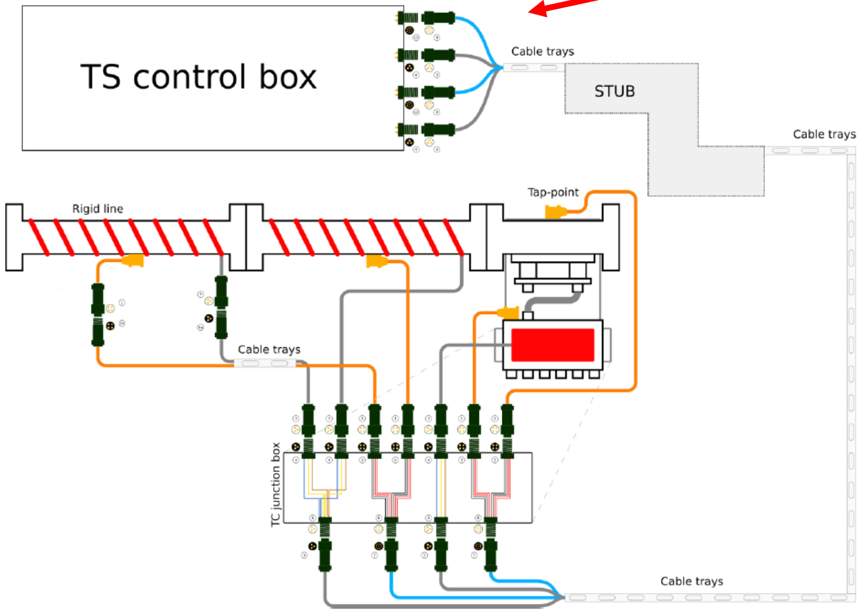


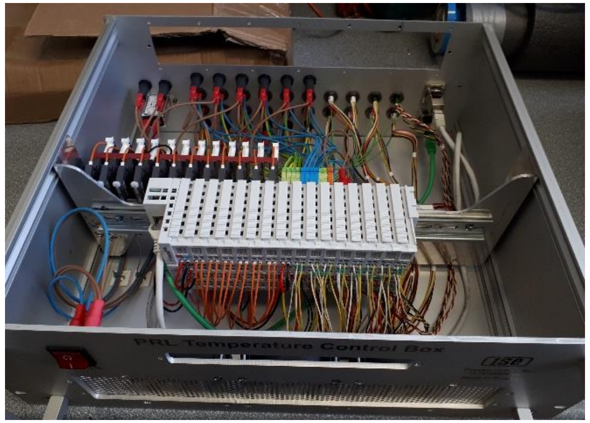


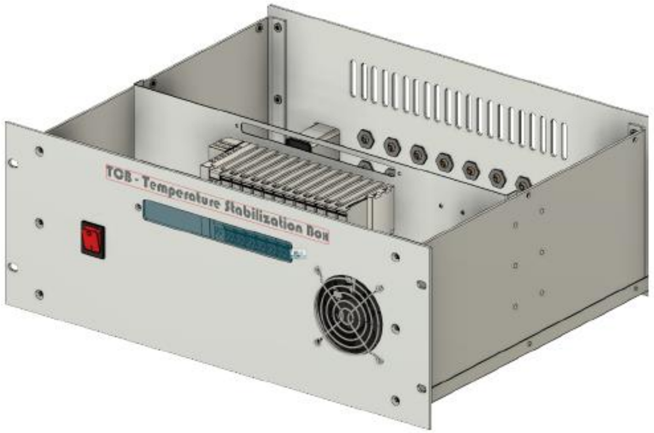
Temperature Control System Components

Simplified scheme of 1 section temperature control

Temperature Control Box







Produced 19 pieces

202 systems
~26 km of cables

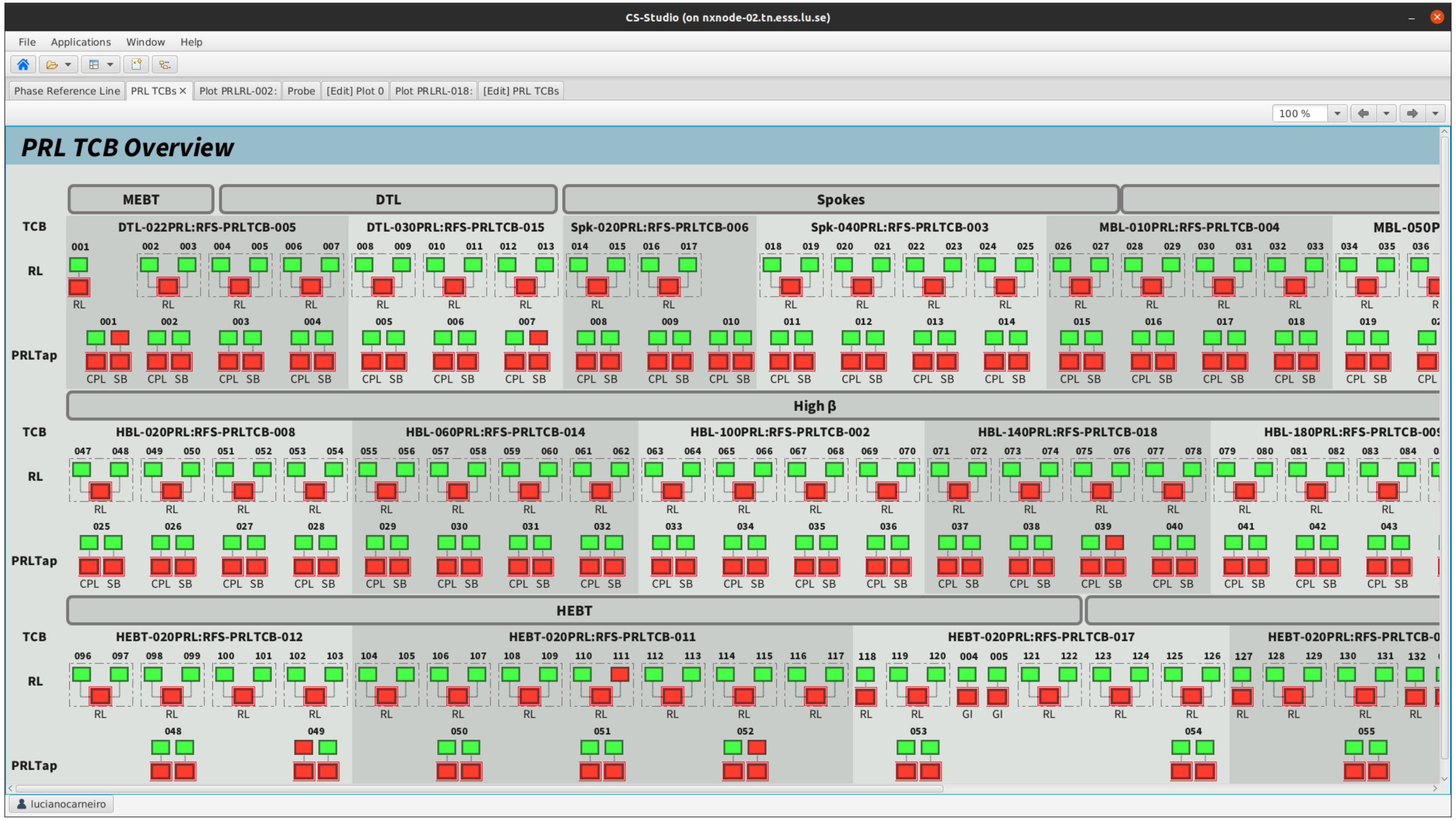
EPICS Implementation

EPICS IOC

- EPID record -> temperature control
- EtherCAT master for communication

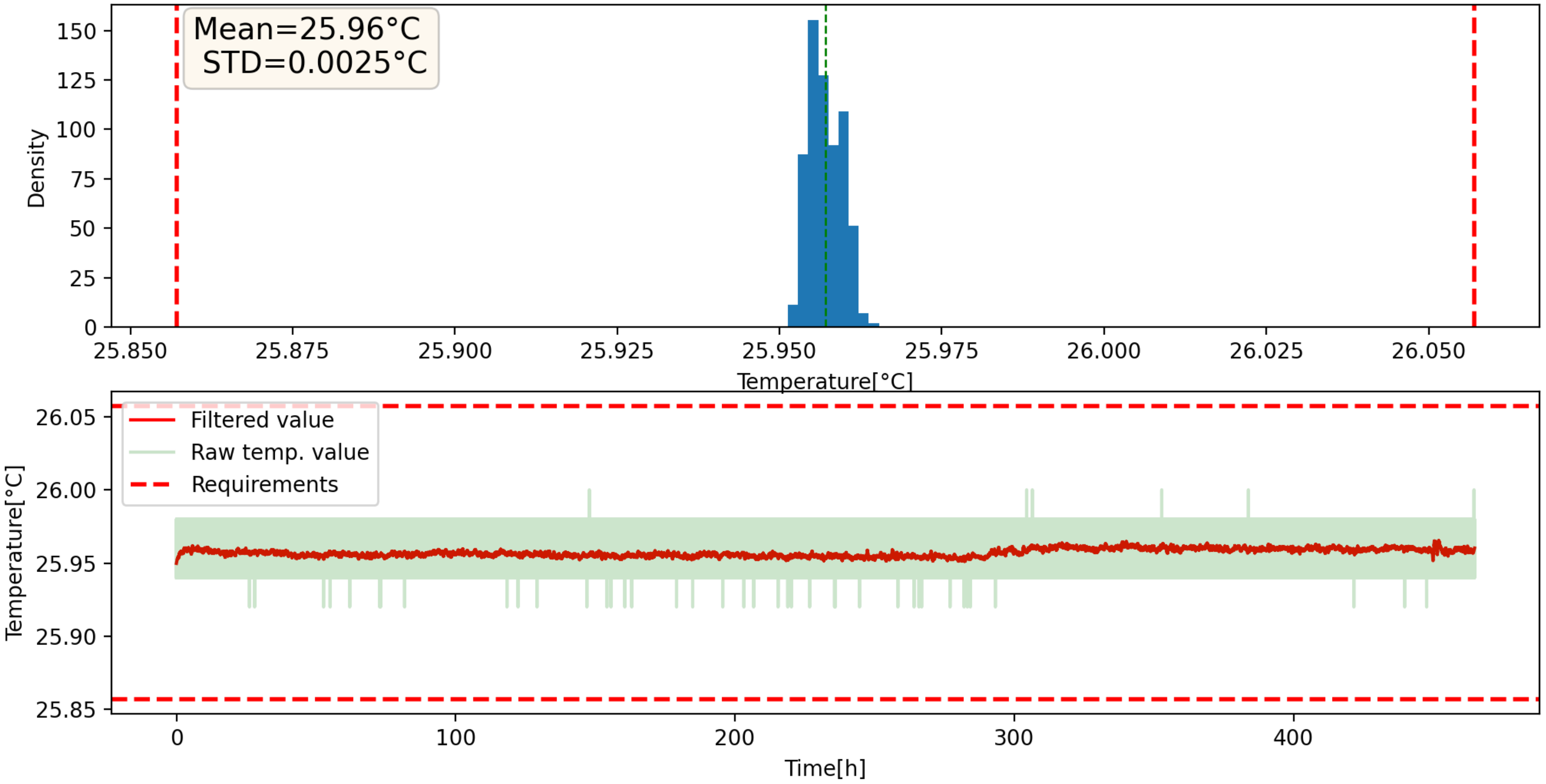
EPICS OPI

- Status of all sensors
- Temperature stabilization loop status
- Set-point
- Temperature history plot



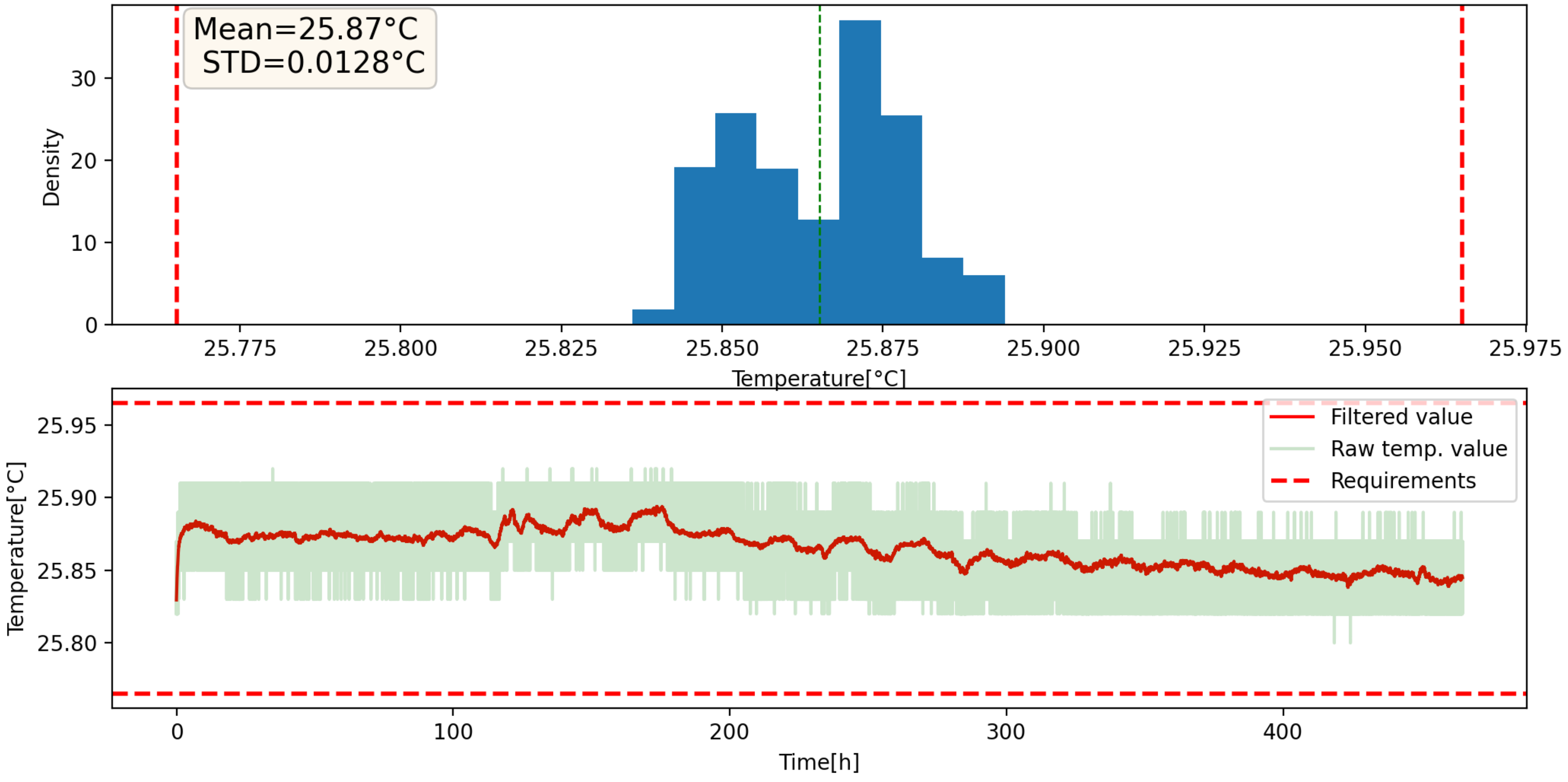
Temperature Control Tests – MBL-090

- Example of **one week** test - all control loops simultaneously
- Typical result for most sections **~0,015ºC p-p**
- Meets requirements

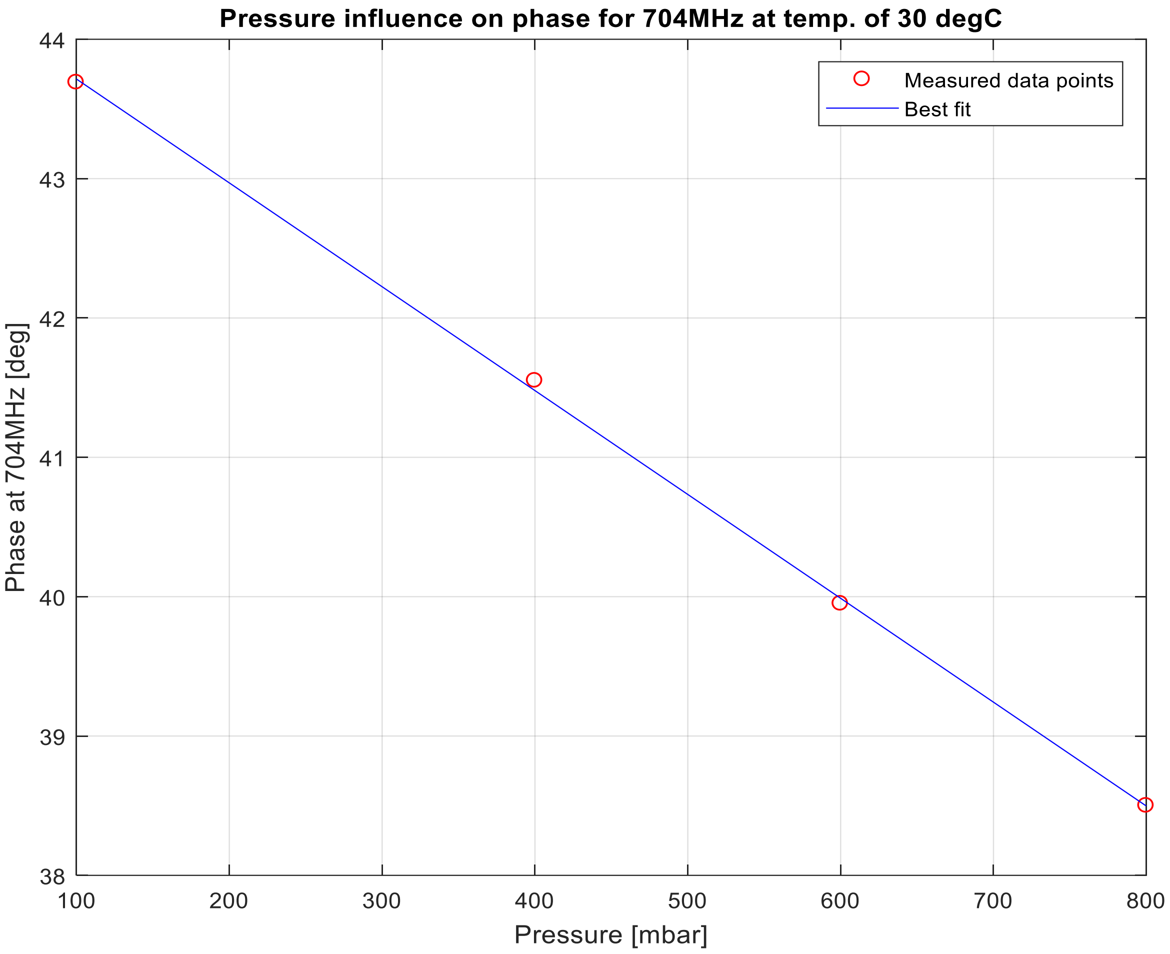


Temperature Control Tests – DTL Section

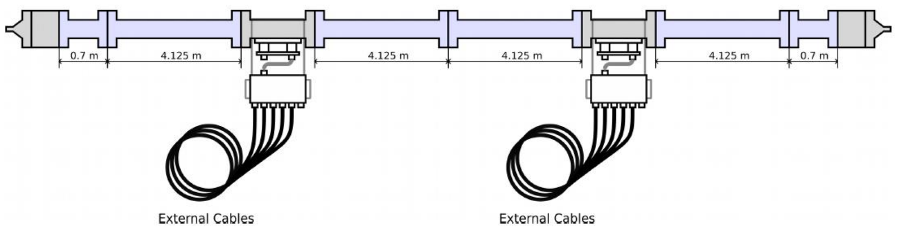
- Example of **one week** test - all control loops running simultaneously
- The **worst case ~0,05°C p-p**
- Meets requirements with significant margin



Gas Pressure Influence on Phase

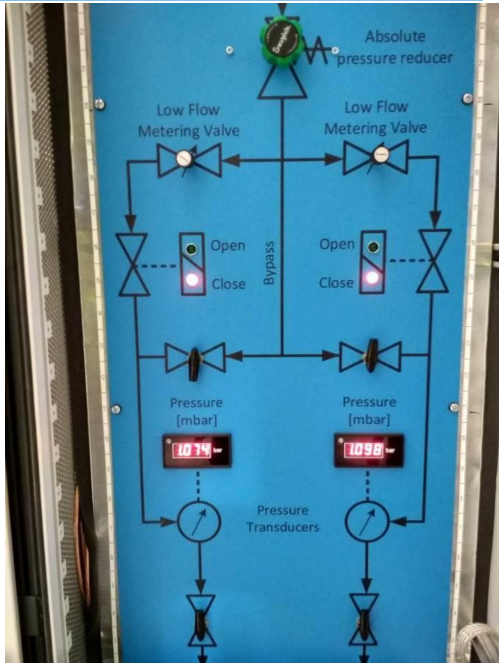


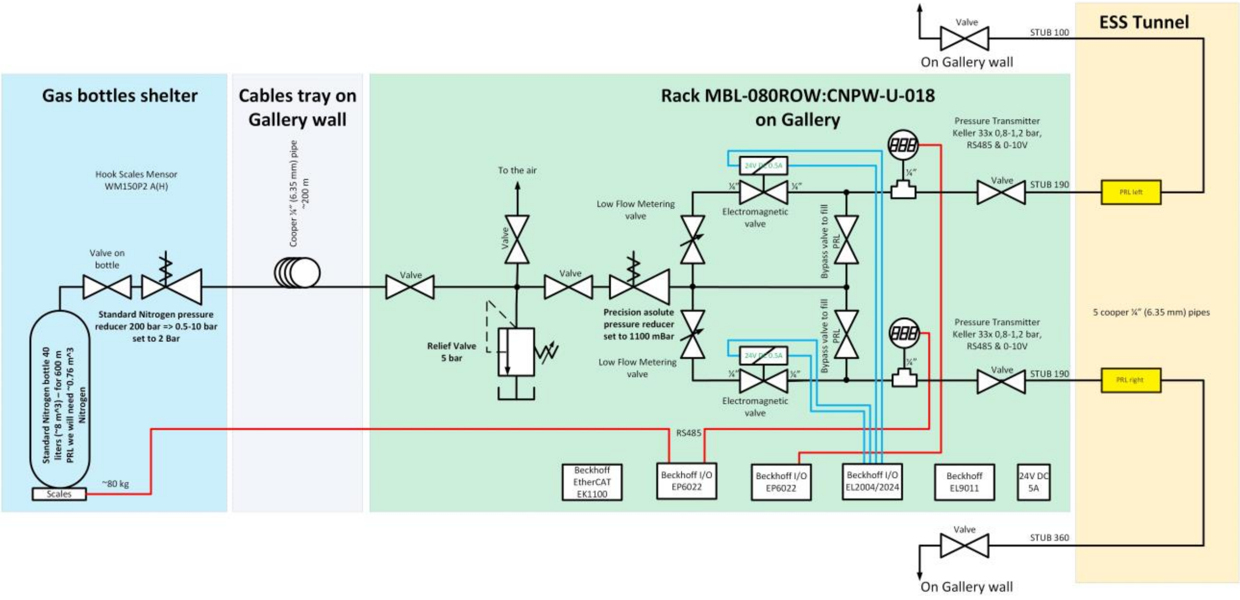
- **Measured round trip phase change in the PRL prototype (2x18.7 m)**
- Temperature Stabilized
- **700 mbar pressure change applied**
- **~5 ° p-p phase change for 37.4 m**
- Estimated ~0.11 °/mbar for 600 m
- Need to stabilize PRL pressure to max 18 mbar.
- Assumed 5 mbar for the design



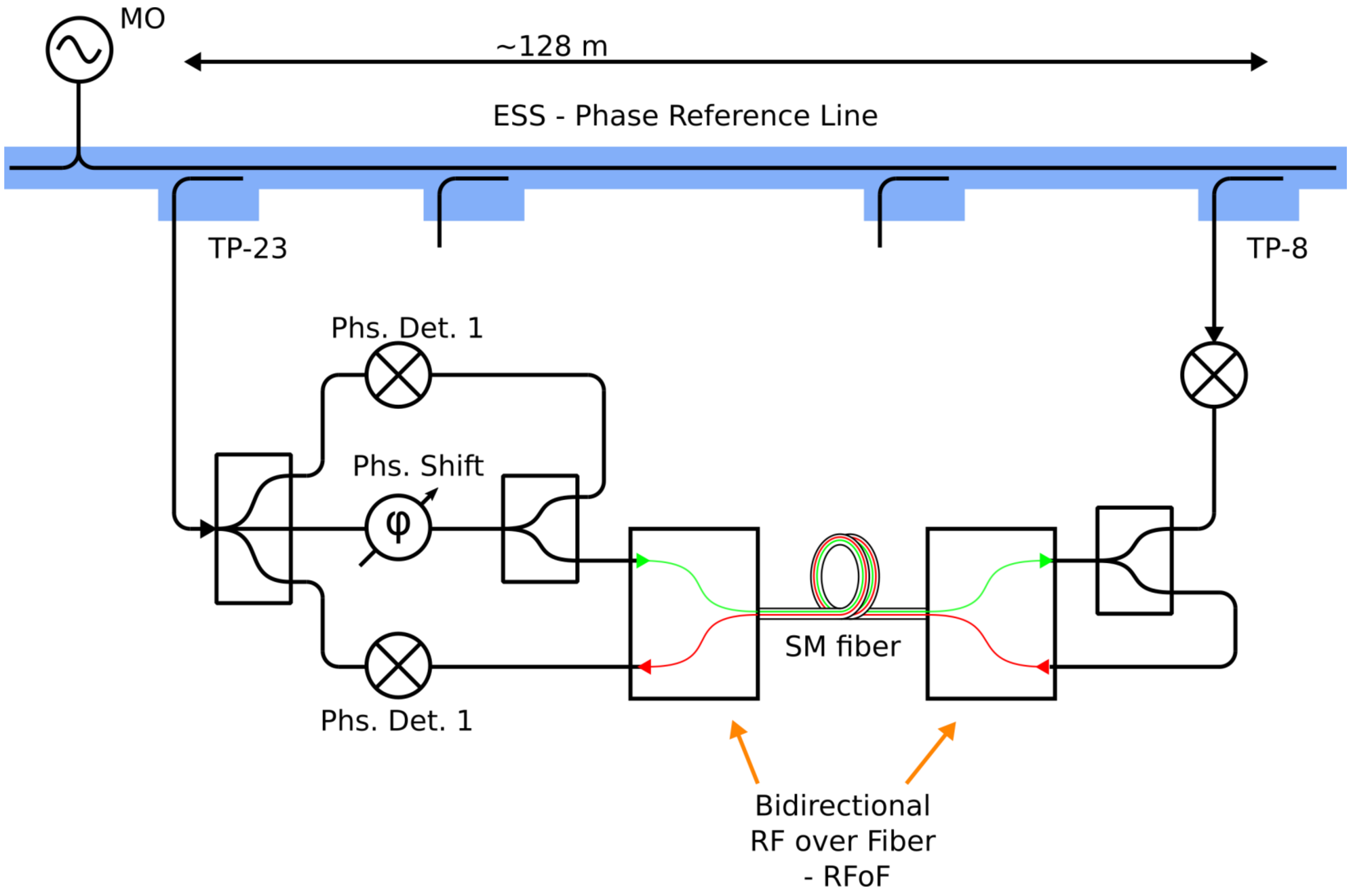
Gas Pressure Stabilization

- Line filled with Nitrogen to remove humidity
- Required and achieved +/- 1 mbar pressure stability
- Gas bottles and valves allowing to separately stabilize and fill in both PRL branches



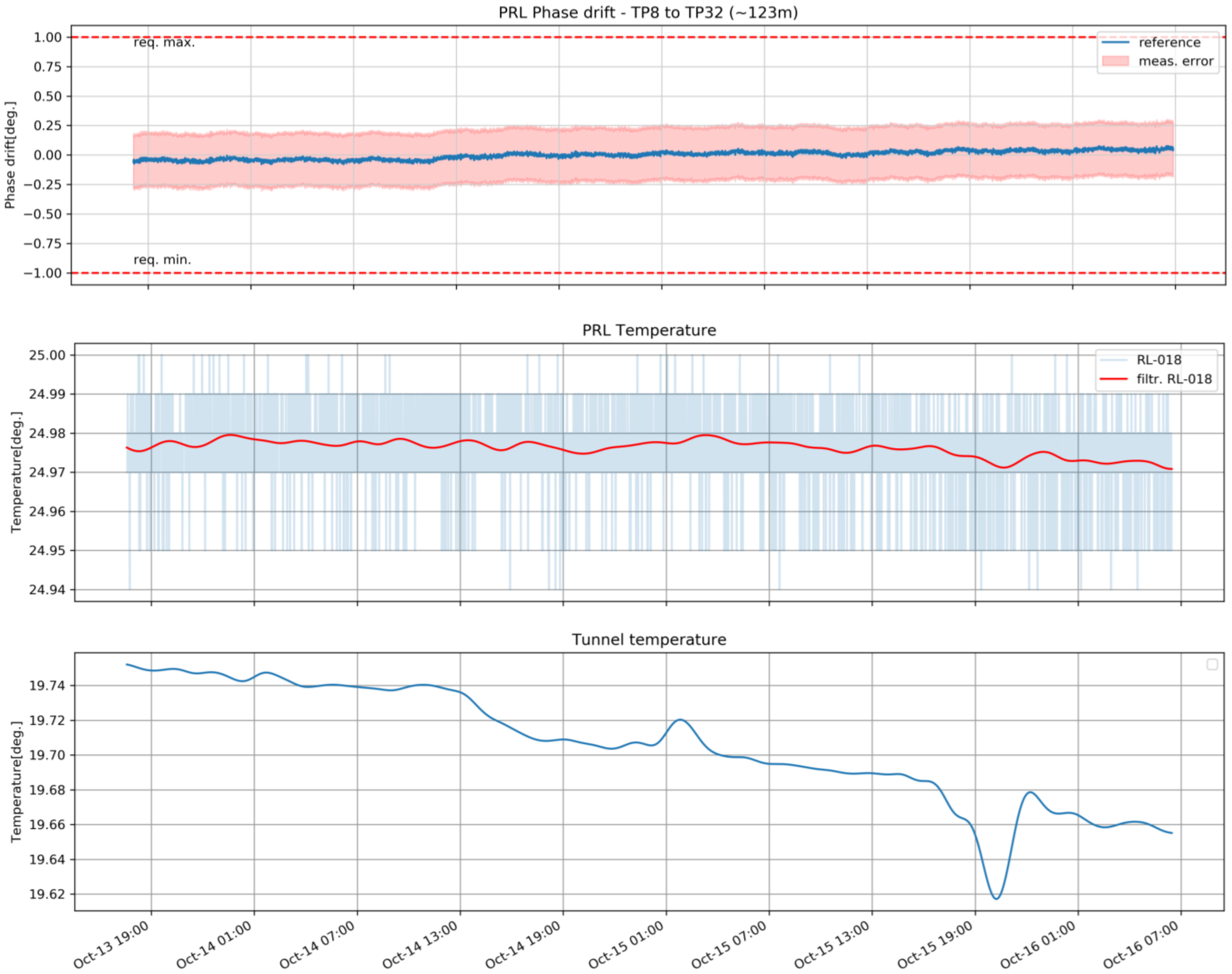


PRL Drift Performance Test Setup



- Phase change measured between TP8 and TP32 (123 m distance
- Maximum possible distance until now
- Installed temporary low-drift (but noisy!) fiber link

Temperature Stability and Phase Drift @ 704 MHz



- Duration 60h
- **Temperature change (mid section) 0.01 ^{o}C p-p**
- **Phase drift: 0.12 ^{o} p-p**
- Requirement: 2.0 ^{o} p-p

Installation Summary

System was installed including:

- Hanging fixtures with rollers allowing to accommodate for thermal system expansion, cable shelves
- Tap Points (58)
- Temperature Control Boxes (19) - **202 temperature control loops**
- Cables **(355 connections, 26 km of cables)**
- Gas pressure stabilization system
- MO to Tunnel connection including 200 W power amplifiers and active drift compensation system (PDC)

Performance Summary

- Power levels within specs
- Drift compensation in the link between MO and tunel 0.15 ^{o}C p-p (waiting for opportunity to measure in the tunnel)
- **Phase drift: 0.12 ^{o} p-p** and **temperature change of 0.01 ^{o}C p-p** at 123 m distance
- Extrapolating drift to 600m -> 0,58 ^{o} p-p (required 2 ^{o} p-p)
- Preparing for long-term tests at the entire PRL length including pressure influence
- Installation of permanent drift monitoring system in progress see poster by D. Sikora

Thank you for attention!

Thanks to all contributors to the system design and installations!

Adam Abramowicz, Anirban Krishna Bhattacharyya, Jerzy Berliński, Bo Bernhardsson, Łukasz Czuba, Grażyna Fistek, Luciano Carneiro Guedes, Paweł Jatczak, Morten Jensen, Michał Kalisiak, Mateusz Lipiński, Maria Mielnik, Krzysztof Oliwa, Björn Olofsson, Radosław Papis, Dominik Sikora, Anders Sunesson, Maciej Urbański, Wojciech Wierba, Rihua Zeng, Mateusz Żukociński, (hope nobody was forgotten…)